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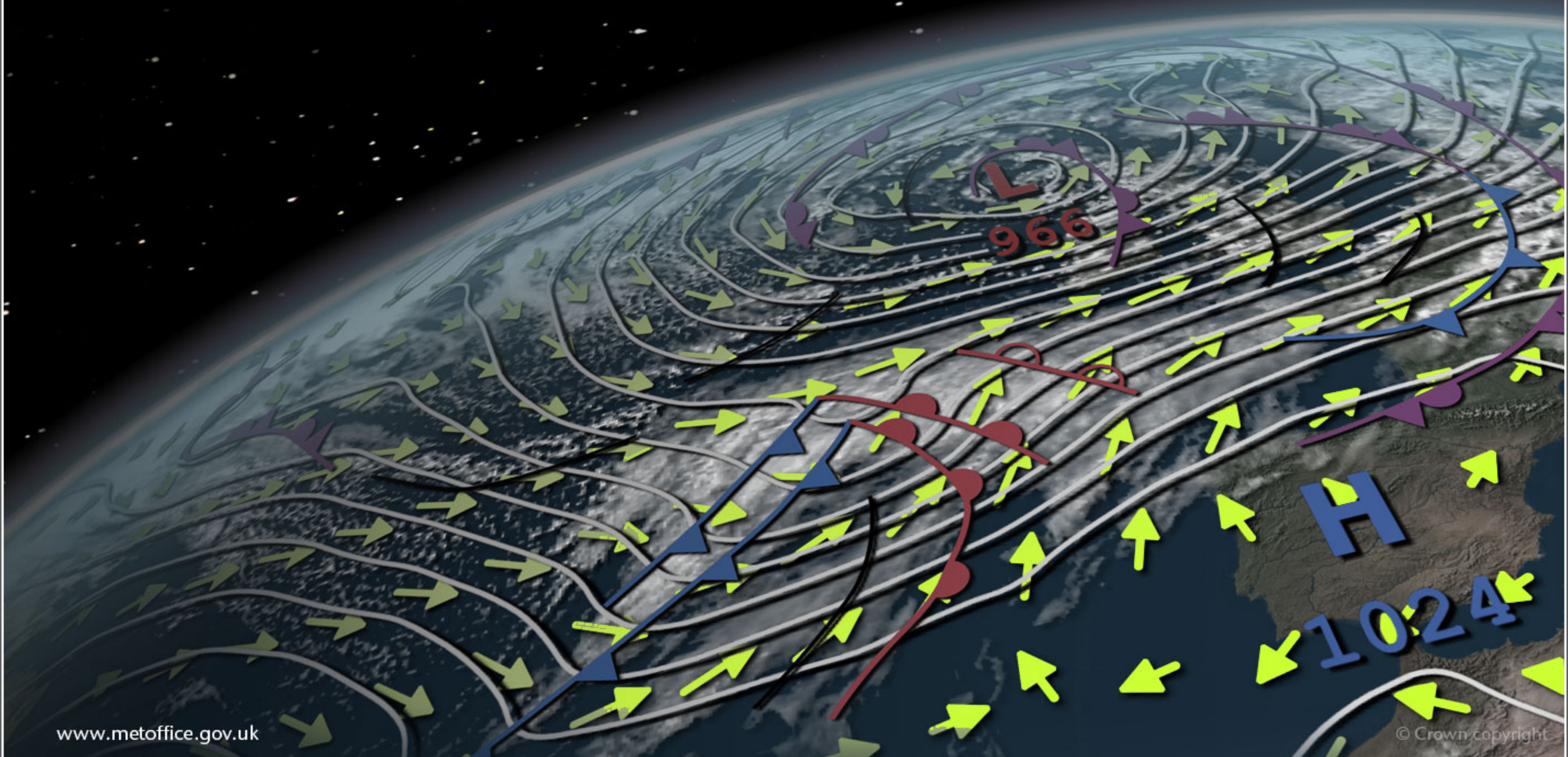
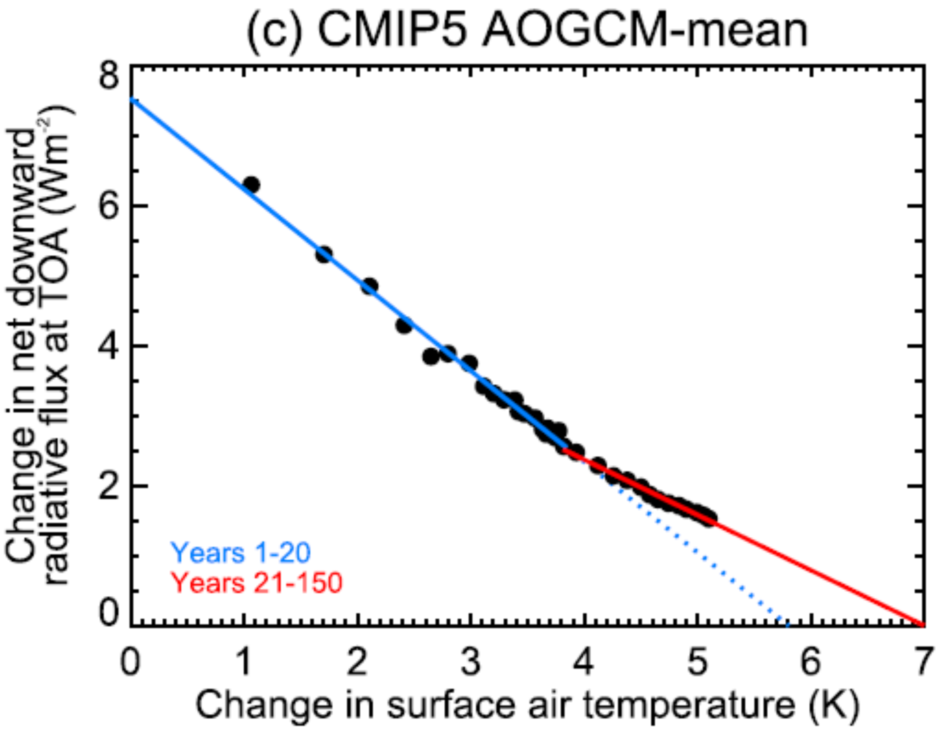
Inconstant feedbacks & their dependence on tropical pacific warming patterns

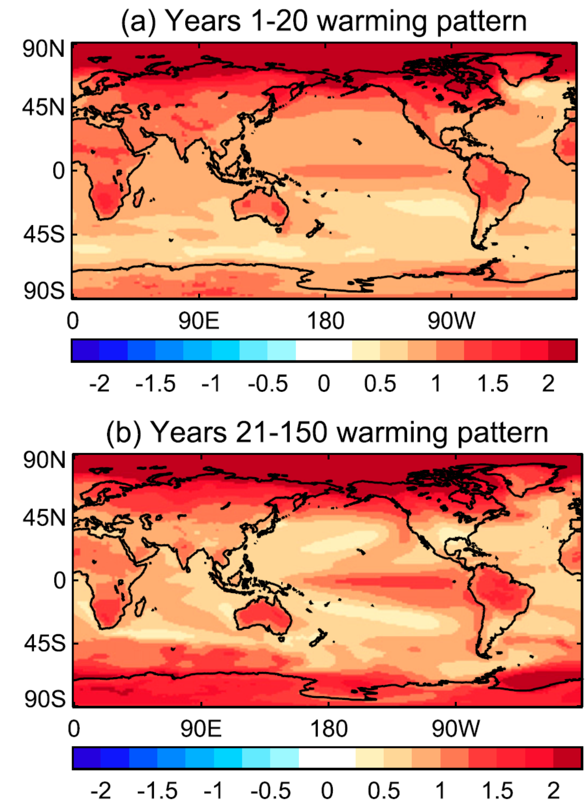
Timothy Andrews with thanks to Mark Webb & Jonathan Gregory.

Earth Radiation Budget Workshop, ECMWF, Reading 2016



Evolving SST patterns and radiative feedbacks under abrupt4xCO_2





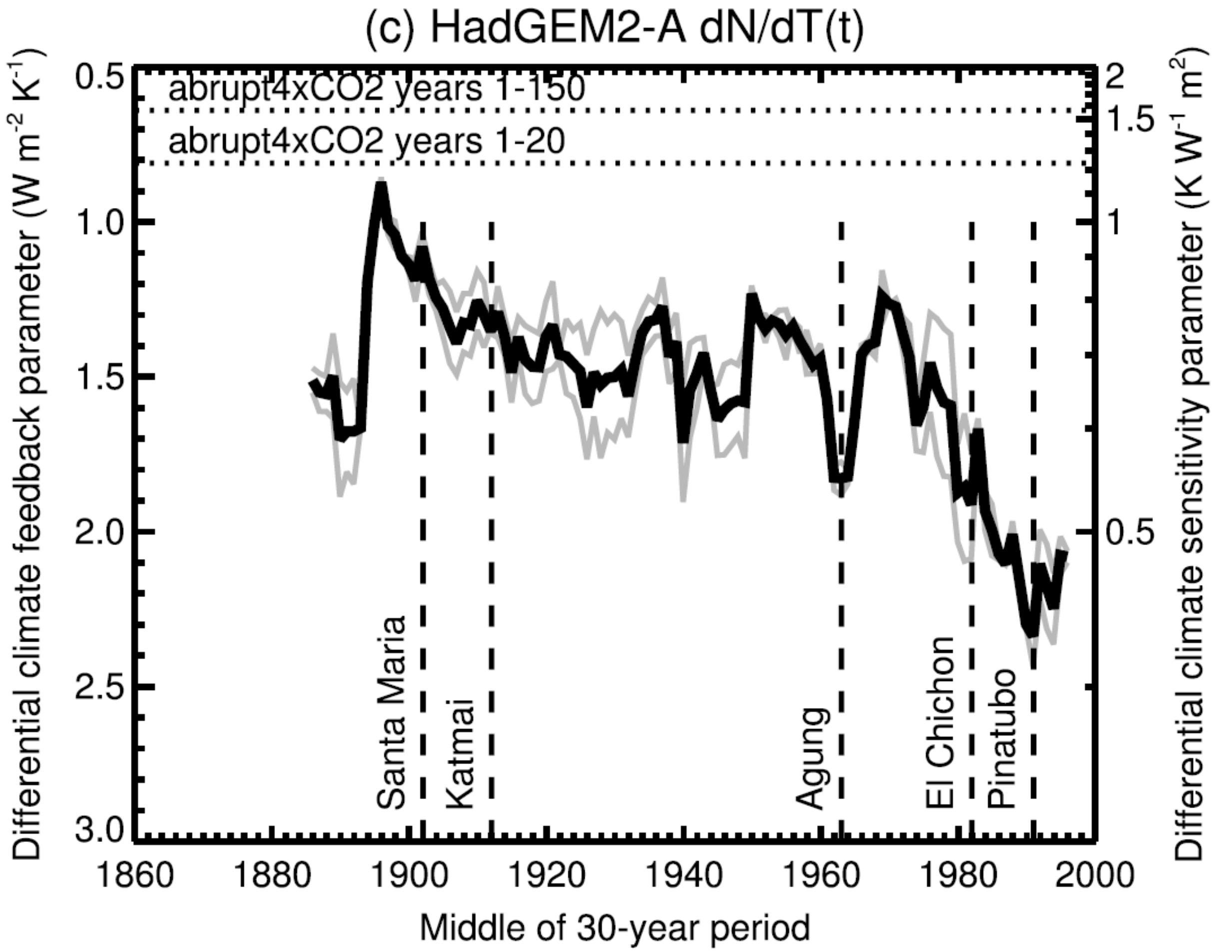
- The surface warming pattern is not constant, e.g. delayed east tropical Pacific and Southern Ocean warming.

- Atmospheric feedbacks change with the pattern of warming, giving more positive feedbacks (shallower slope) after ~20yrs – involves local and nonlocal processes.

- Largely robust across CMIP5 AOGCMs. All feedbacks show some change, though the largest increase is in cloud feedback.

Andrews, T., J.M. Gregory and M.J. Webb, 2015: The dependence of radiative forcing and feedback on evolving patterns of surface temperature change in climate models. J. Climate, 28, 1630-1648, doi:10.1175/JCLI-D-14-00545.1.

Multi-decadal variability in historical feedbacks



- HadGEM2-A forced with observed historical SST variations simulates multi-decadal variations in climate feedbacks, mostly from clouds.

- Feedback is always larger (climate sensitivity smaller) than that found in 4xCO2 experiments, particularly in most recent decades.

Gregory, J.M., and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical period. Geophys. Res. Lett., 43, 3911–3920, doi:10.1002/2016GL068406.

Approach

Inconstant feedbacks appears to be an issue in GCMs, both in idealised CO_2 experiments and those traceable to historical climate change.

- What is going on? What are the physical processes/mechanisms?

One way to address this is to run atmosphere only experiments forced with various dSST patterns, analogous to how feedbacks have been diagnosed over many years using initially +2K SST experiments (e.g. Cess et al., 1996), and more recently amip +4K in CMIP5/CFMIP2 (Bony et al., 2011).

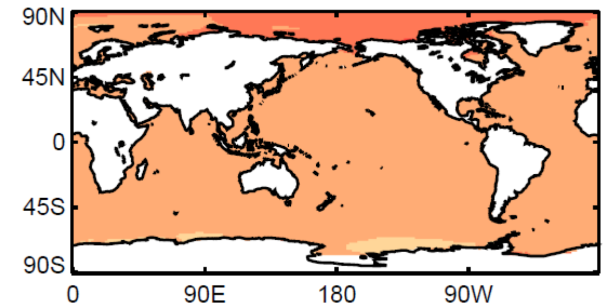
Here I expand the amip+4K approach, i.e. run an amip experiment (1979-2008 with observed SST and sea-ice variations) with SSTs increased such that the global-mean dSST=4K, with various dSST patterns derived from AOGCMs and observed climate change.

Experiments with HadGEM2

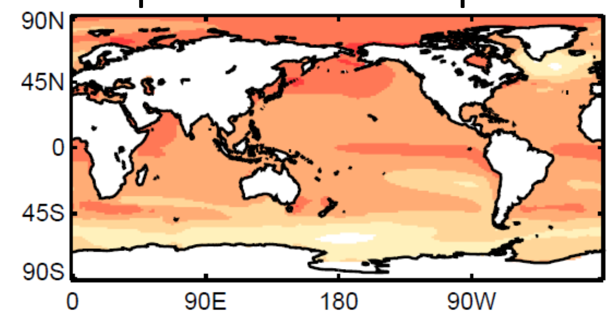
Experiment	Description
amip4Kuniform	+4K to all SSTs
amip4Kfuture	dSST(x,y) from end of 1%CO2 AOGCMs
amip4Kfast	dSST(x,y) from first 20yrs of abrupt4xCO_2
amip4Kslow	dSST(x,y) from 21-150yrs of abrupt4xCO_2
amip4K20thC	dSST(x,y) from 1900-2012 amip BC SSTs

All have global-mean dSST=4K and are run for 30 years, as per the CMIP5/CFMIP3 amip4K uniformed & future experiments.

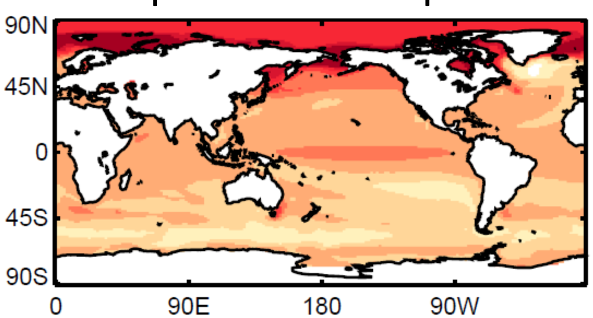
amip4K uniform dSST pattern



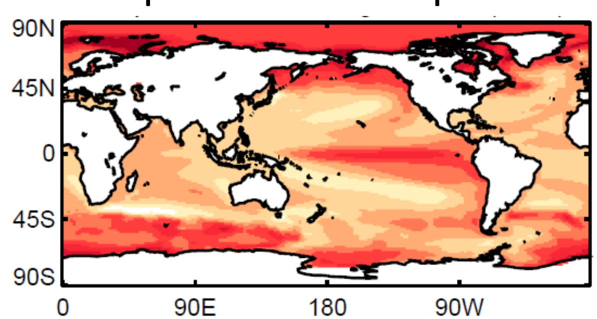
amip4K future dSST pattern



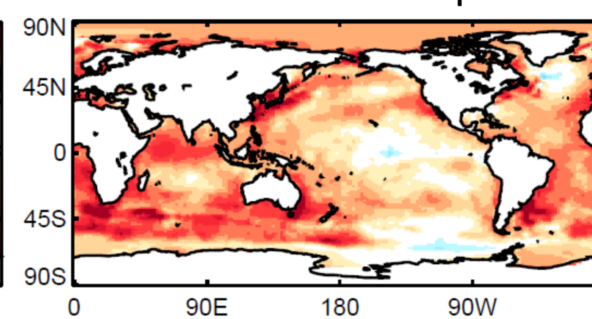
amip4K fast dSST pattern

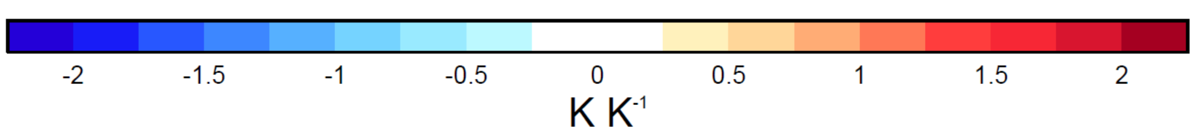


amip4K slow dSST pattern

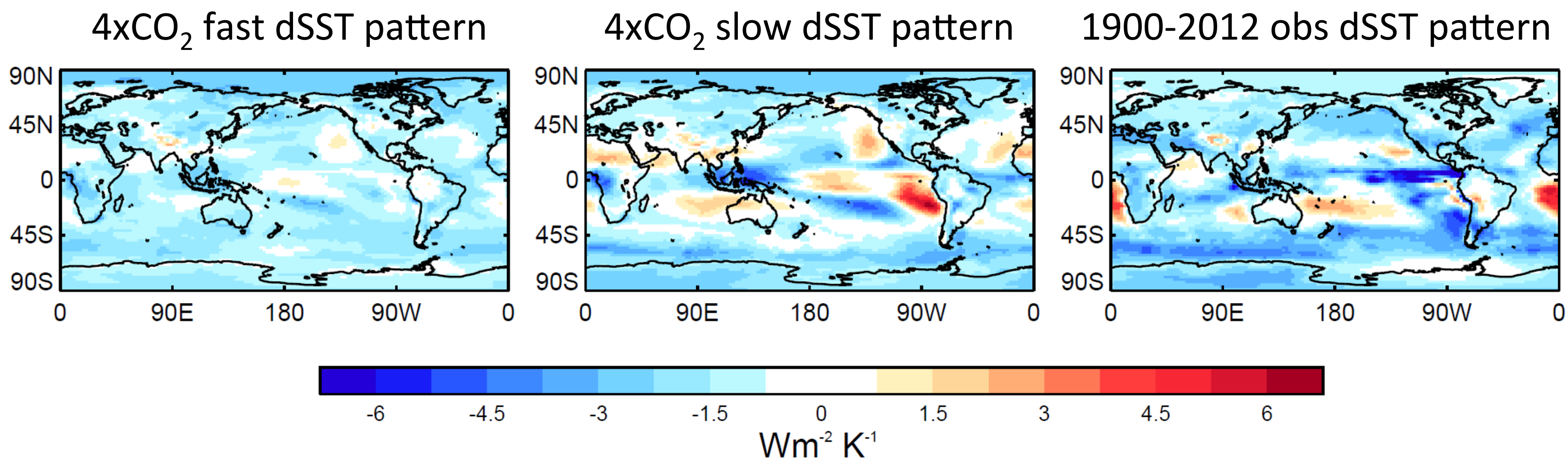


1900-2012 obs dSST pattern





Atmospheric feedbacks to various dSST patterns



dN/dT = -1.3 $Wm^{-2}K^{-1}$

ECS ~ 3.5K

dN/dT = -1.0 $Wm^{-2}K^{-1}$

ECS ~ 5K

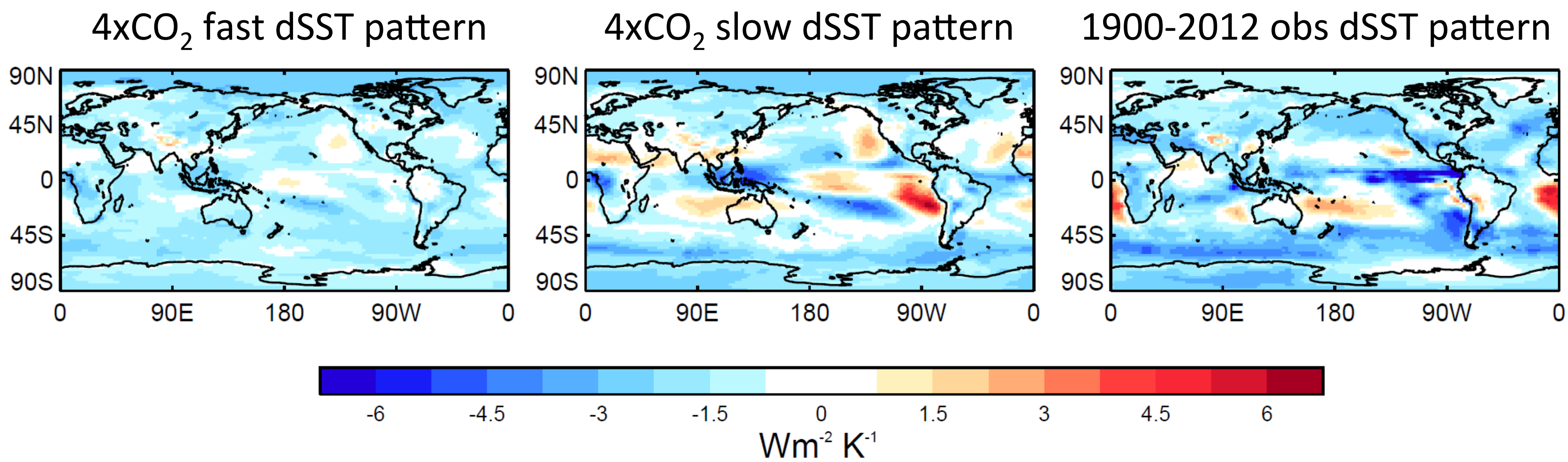
dN/dT = -1.6 $Wm^{-2}K^{-1}$

ECS ~ 2.7K

- Reproduces the curvature in the Gregory plot, i.e. amip4K*slow* has more positive feedbacks (larger ECS) than amip4K*fast*

- 20th century warming pattern gives small ECS.

Atmospheric feedbacks to various dSST patterns



$dN/dT = -1.3\ Wm^{-2}K^{-1}$

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ECS ~ 2.7K

Climate sensitivity nearly halved just by changing warming pattern, note no change in model physics!

Feedback decomposition with radiative kernels

Experiment	Net	Planck	LR	WV	WV+LR	Albedo	Cloud	Residual
amip4Kuniform	-1.31	-3.19	-0.85	1.75	0.90	0.09	0.49	0.40
amip4Kfuture	-1.37	-3.22	-1.01	1.88	0.87	0.09	0.45	0.44
amip4Kfast	-1.31	-3.18	-0.81	1.76	0.95	0.10	0.44	0.38
amip4Kslow	-0.98	-3.16	-0.58	1.64	1.06	0.09	0.60	0.42
amip4K20thC	-1.61	-3.20	-1.06	1.82	0.76	0.08	0.40	0.35
Range (max–min)	0.63	0.06	0.48	0.24	0.30	0.02	0.20	0.09

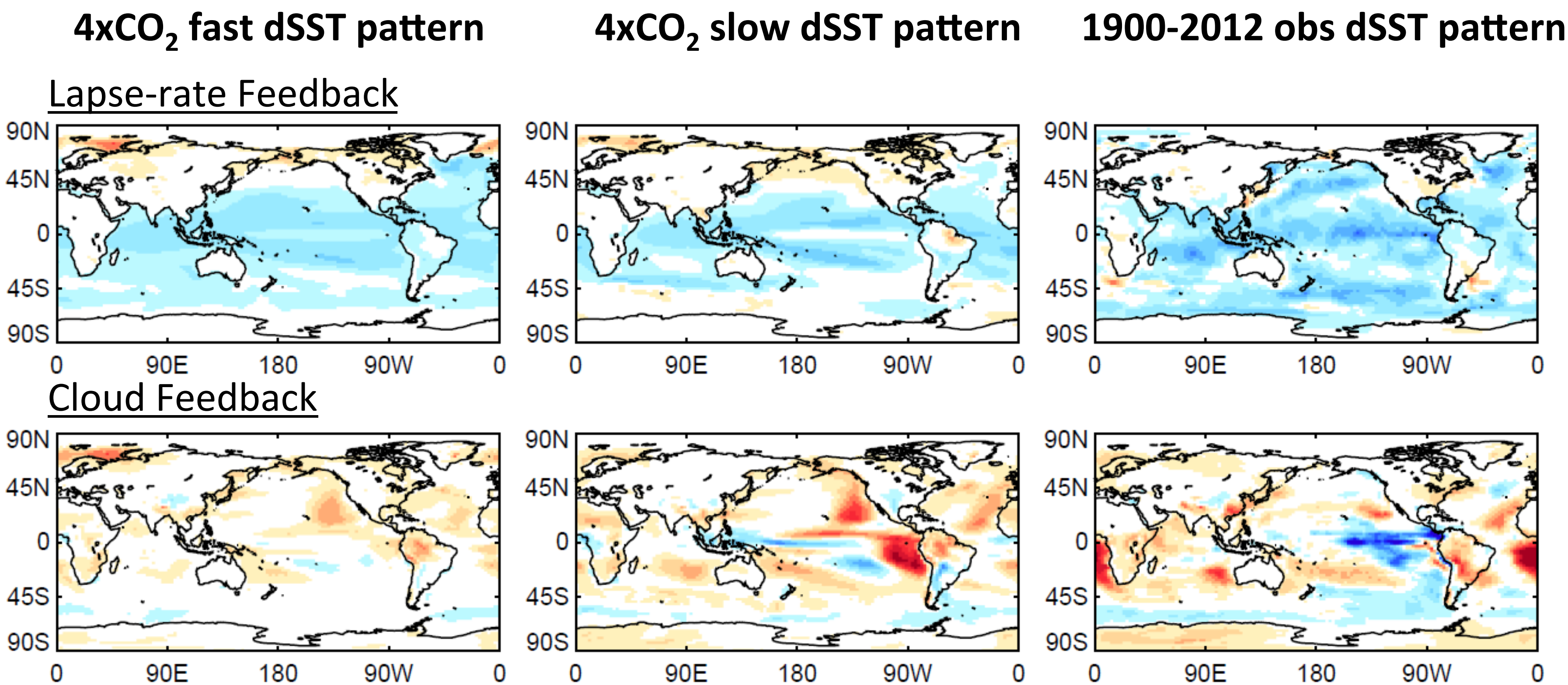
• Planck and albedo feedback robust (though note sea-ice changes excluded).

• Largest dependence on warming pattern is from lapse-rate feedback, though to some extent compensated for by changes in water-vapour feedback.

• Large dependence in cloud feedback, very strong in amip4Kslow and weak when model forced with observed dSST.

• Focus on cloud and lapse rate feedbacks, since they vary the most, explain most of the variation in net feedback (r>0.9) and are correlated with each other (r=0.9, suggesting a common mechanism)

Atmospheric feedbacks to various dSST patterns



• Spread in cloud feedback is dominated by regions of marine stratocumulous, for example very large positive feedback in amip4Kslow, in contrast little to no feedback in amip4Kfast, and negative cloud feedback in amip4K20thC.

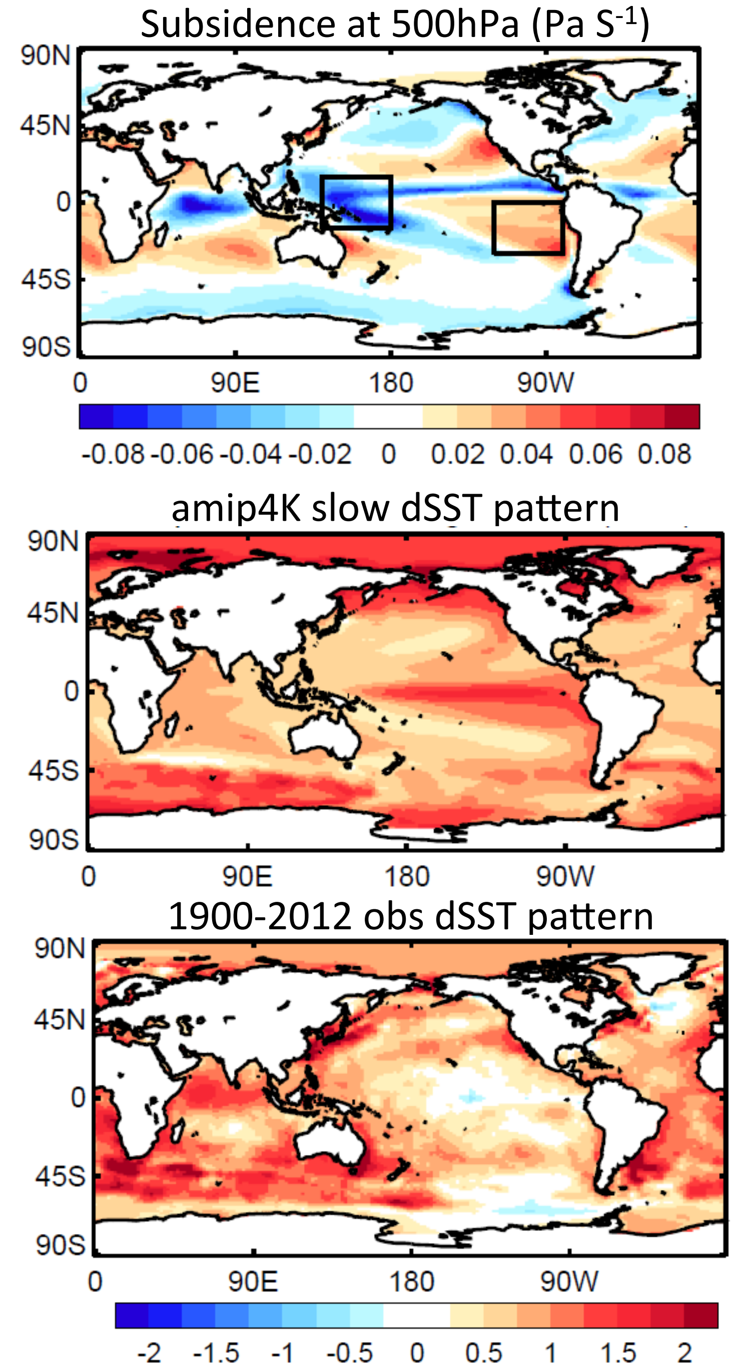
• Lapse-rate feedback also varies in the tropical Pacific, but also to some extent in the mid latitudes.

Proposed mechanism

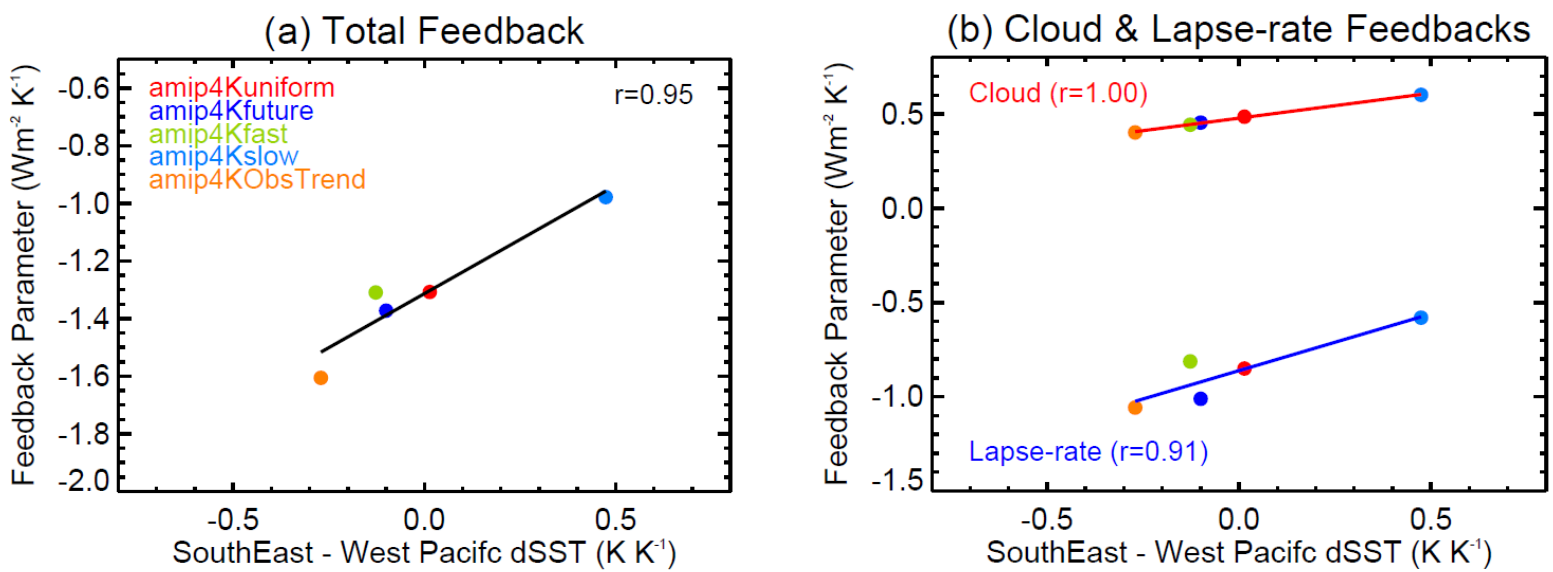
Marine low cloud changes controlled by a thermodynamic response to surface warming and a response to lower tropospheric stability ($LTS=\theta_{700}-\theta_{srf}$) changes (e.g. Qu et al., 2015, JGR).

If tropical warming is focused in regions of strong subsidence and low cloud, such as the southeast tropical Pacific, then warming will be trapped under the inversion that caps the boundary layer. Results in a *large positive thermodynamic cloud feedback*, but it also reduces LTS since little impact at 700mb, entraining warm and dry air from above, further reducing low cloud cover. Since warming is trapped at lower levels this also results in a *weak lapse-rate feedback*.

In contrast, if warming is focused in regions of strong ascent, such as the convective regions of the west Pacific, then warming is efficiently transported to upper levels and throughout the free troposphere. The result is strong warming aloft, *increasing stability and the atmospheric lapse-rate feedback* and increasing LTS in low cloud regions, which *dampens (or even offsets) the thermodynamic positive low cloud feedback to warming*.



Dependence of feedbacks on warming contrast in ascent & descent regions

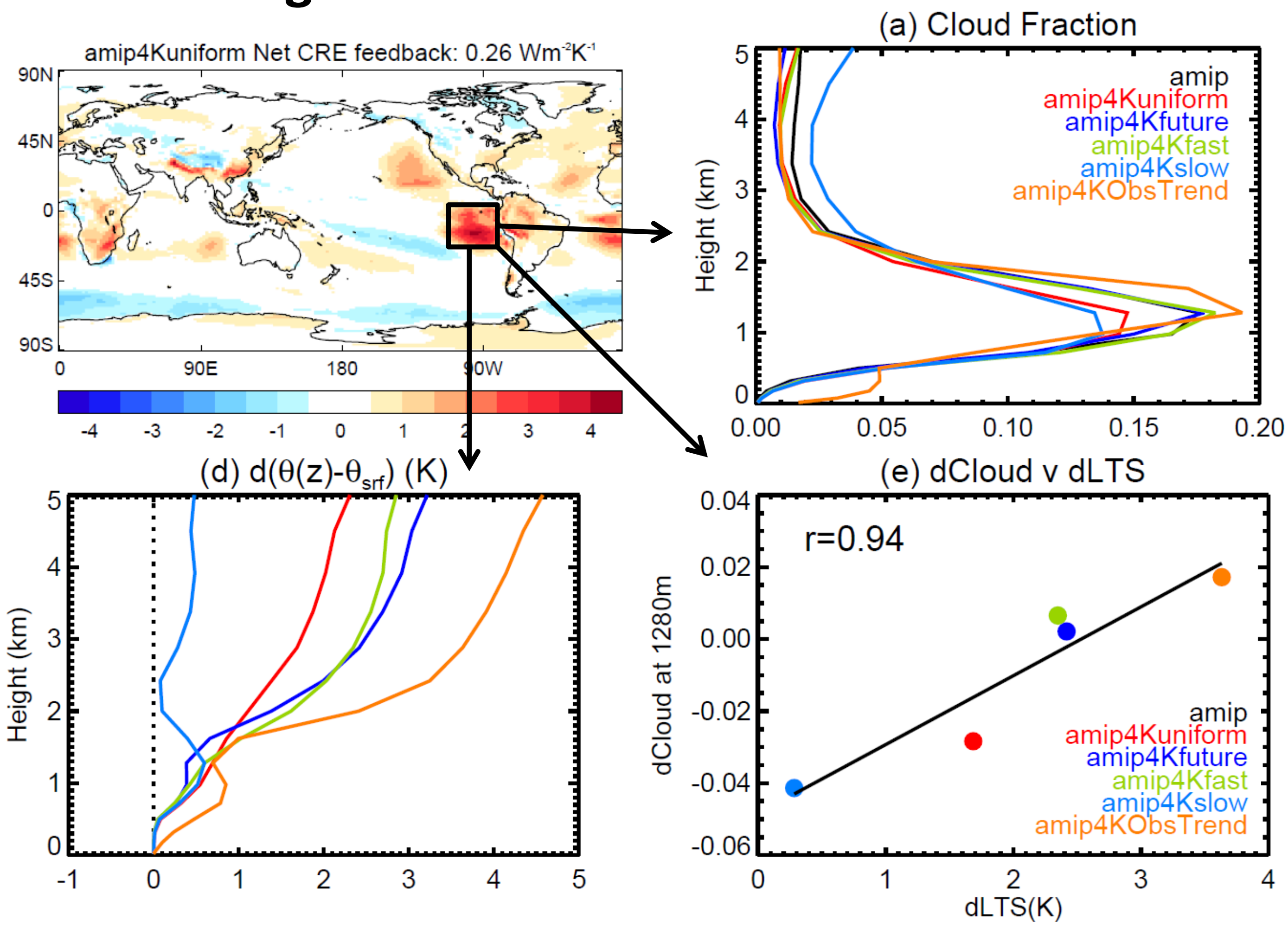


- Simple metric that contrasts the warming in the two regions of strong ascent and descent

  > 0 implies greater warming in south east Pacific (e.g. amip4Kslow), consequently warming trapped in boundary layer, reducing cloud cover and smaller lapse-rate change.

  < 0 implies greater warming west Pacific (e.g. amip4K20thC), consequently smaller low cloud change to local dSST, and larger warming of free troposphere, which increases lapse-rate and LTS of low cloud regions (further dampening cloud change).

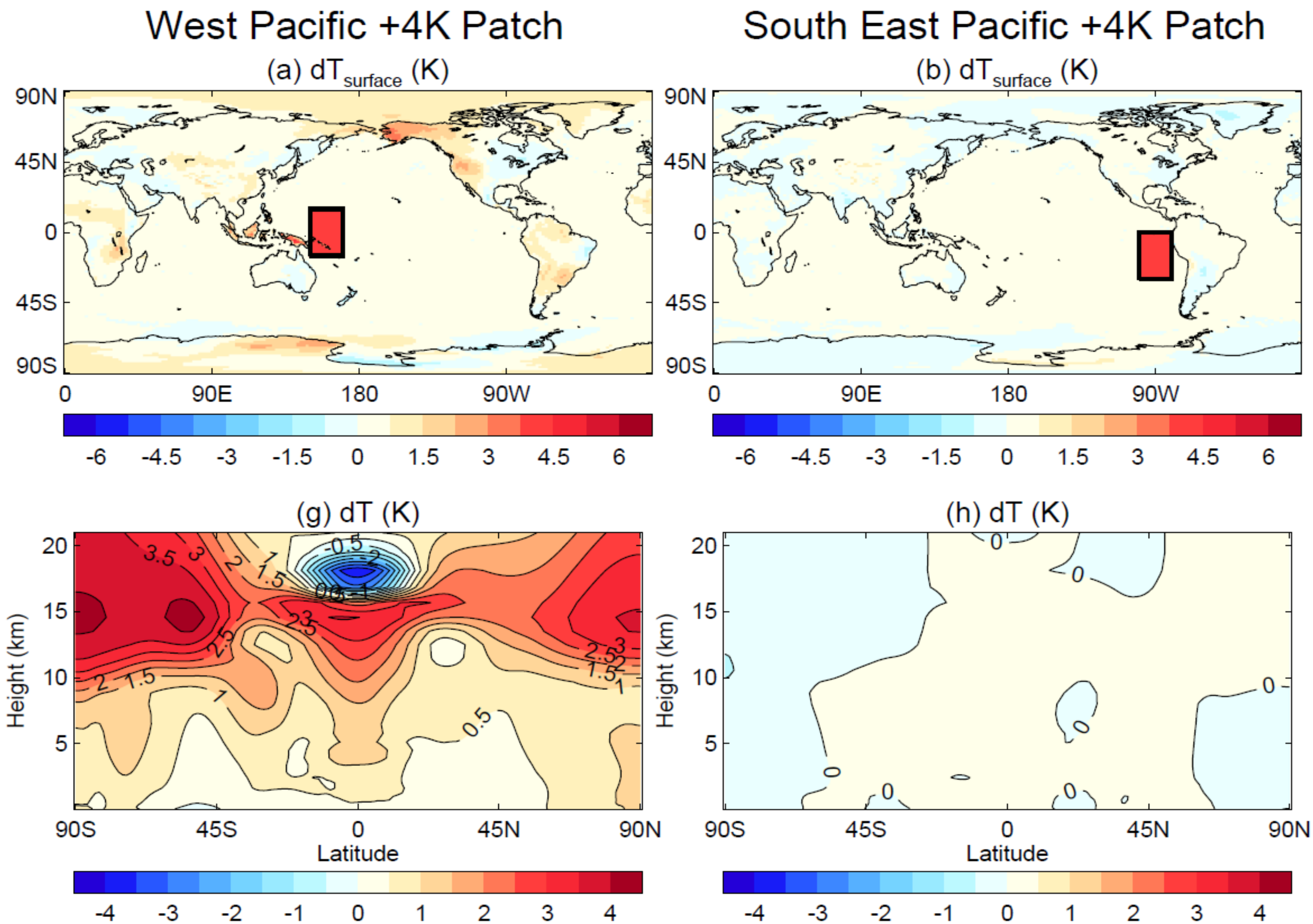
Illustrating the mechanism in marine low clouds



- Low cloud max at ~1-1.5km, sitting under a temperature inversion that caps the boundary layer.

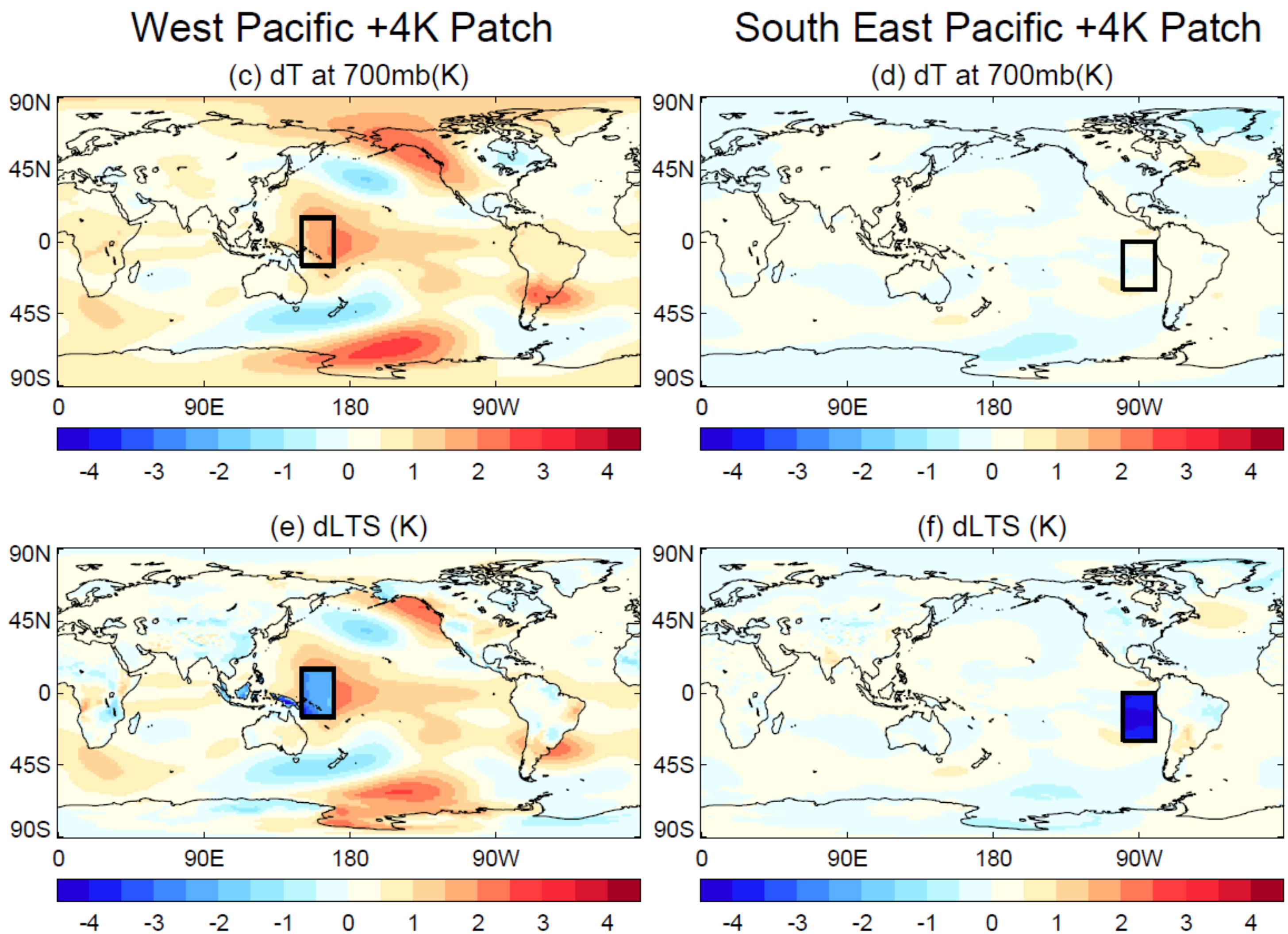
- amip4Kslow warms the most in this region, and shows the biggest reduction in cloud and cloud feedback. amip4K20thC SST warms the least but has largest warming aloft due to strong warming in west Pacific. Consequently biggest increase in stability, increasing LTS which inhibits mixing of drier and warmer air from above, increasing cloudiness.

Testing the impact of South East v West Pacific SST changes



- Surface warming in the South East Pacific is confined to the boundary layer, whereas free tropospheric temperatures strongly respond to West Pacific SST increases, increasing stability widely across the globe.

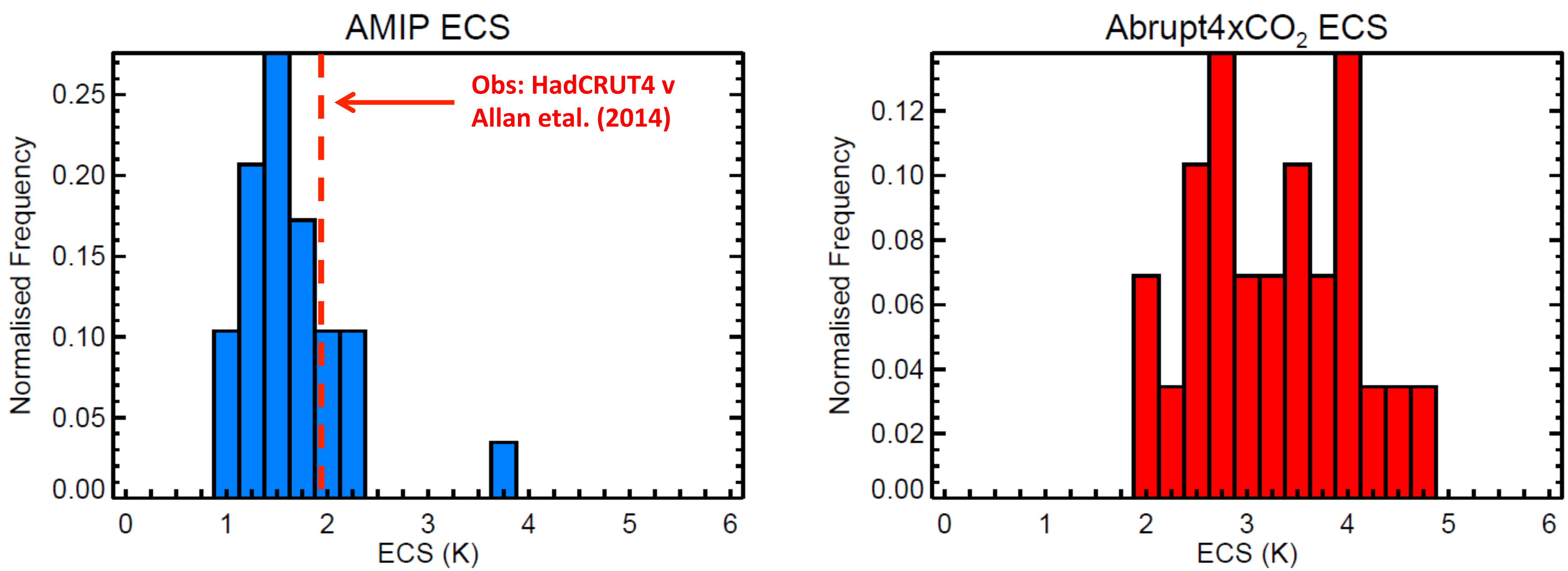
Testing the impact of South East v West Pacific SST changes



- 700mb temperatures respond strongly to west Pacific warming but not south east Pacific.

- Hence LTS and low cloud changes depend on local and remote SST changes, in particular the warming pattern widely across the tropical pacific.

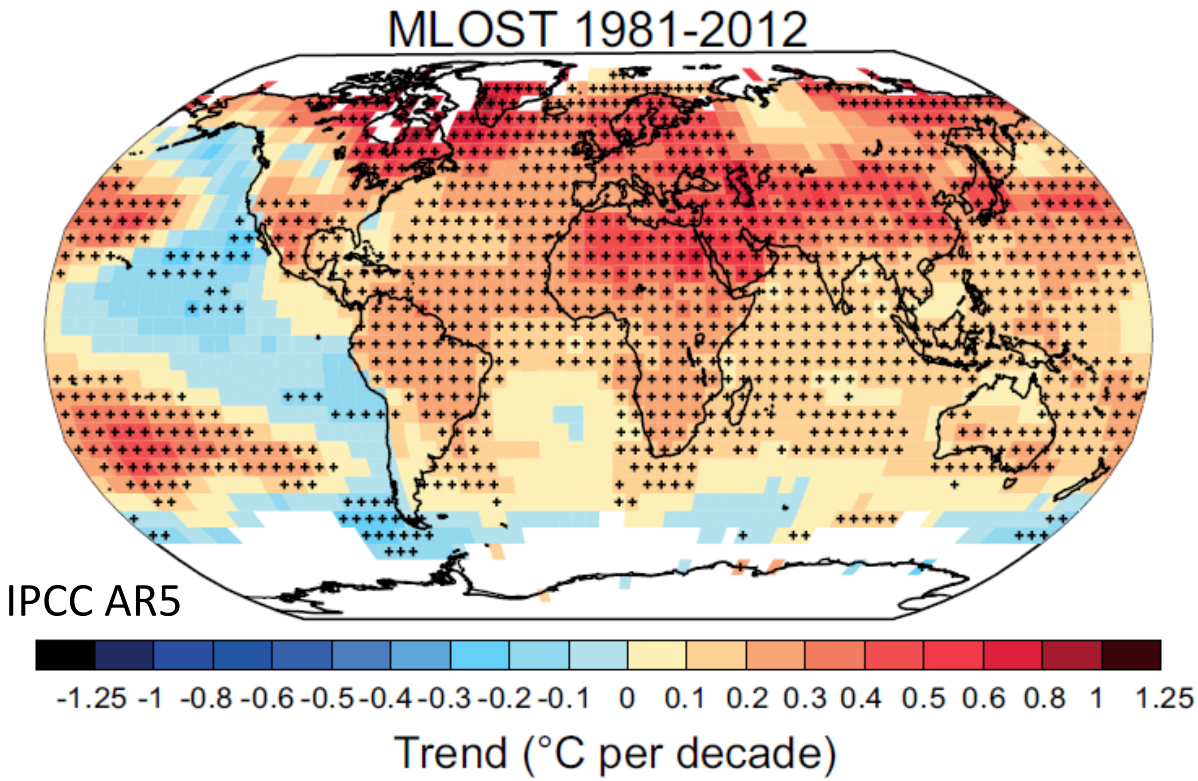
Can this explain low ECS of CMIP5 models during 1979-2008?



- CMIP5 models forced with observed dSST and sea-ice variations from 1979-2008 (amip simulations) simulate large negative feedbacks and very low ECS values (~1-2K) compared to CO2 forced experiments and more uniform warming patterns (Andrews, 2014; Gregory and Andrews, 2016).

- Note no discrepancy with observations when AGCMs are forced with observed dSST and sea-ice variations.

Can this explain low ECS of CMIP5 models during 1979-2008?



- Observed warming over recent decades shows substantial cooling in east tropical Pacific, despite global and west Pacific warming.

- During this period we ought to expect an enhanced negative LR feedback and reduced positive – or even negative – cloud feedback. Both would give a more negative feedback parameter (smaller ECS) compared to more uniform patterns of warming, as we see in the models.

Summary

- Feedbacks are not constant, they vary with the pattern of warming – particularly cloud and lapse-rate feedbacks.

- Targeted AGCM experiments with various SST patterns – traceable to AOGCM transient behaviour and observations – are a valuable tool in understanding the mechanisms and processes related to time varying feedbacks. New experiments in CMIP6 and CFMIP3 designed to look at this across models.

- HadGEM2 experiments reveal that cloud and lapse-rate feedbacks strongly depend on the pattern of warming in the tropical Pacific:

    - When warming is focused in the South East tropical Pacific there is a very strong +ve cloud feedback from marine stratocumulus clouds and weak –ve lapse rate feedback (large ECS)

    - When warming is delayed in the South East tropical Pacific, and enhanced in West Pacific, free tropospheric warming is large while local dSST is small, thus giving a strong –ve lapse rate feedback and stability change that reduces the +ve cloud feedback (small ECS)

- Recent decadal temperature change shows cooling trends in the East Pacific, hence feedbacks and climate sensitivity estimates derived from this period will be biased low compared to long term trends where we expect less heterogeneous warming patterns.